III. *On the Mechanical Equivalent of Heat.* By JAMES PRESCOTT JOULE, *F.C.S., Sec. Lit. and Phil. Society, Manchester, Cor. Mem. R.A., Turin, &c.* Communicated by MICHAEL FARADAY, *D.C.L., F.R.S., Foreign Associate of the Academy of Sciences, Paris, &c. &c. &c.*

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"Heat is a very brisk agitation of the insensible parts of the object, which produces in us that sensation from whence we denominate the object hot; so what in our sensation is *heat*, in the object is nothing but *motion*."—LOCKE.

"The *force* of a moving body is proportional to the square of its velocity, or to the height to which it would rise against gravity."—LEIBNITZ.

IN accordance with the pledge I gave the Royal Society some years ago, I have now the honour to present it with the results of the experiments I have made in order to determine the mechanical equivalent of heat with exactness. I will commence with a slight sketch of the progress of the mechanical doctrine, endeavouring to confine myself, for the sake of conciseness, to the notice of such researches as are immediately connected with the subject. I shall not therefore be able to review the valuable labours of Mr. FORBES and other illustrious men, whose researches on radiant heat and other subjects do not come exactly within the scope of the present memoir.

For a long time it had been a favourite hypothesis that heat consists of "a force or power belonging to bodies*," but it was reserved for Count RUMFORD to make the first experiments decidedly in favour of that view. That justly celebrated natural philosopher demonstrated by his ingenious experiments that the very great quantity of heat excited by the boring of cannon could not be ascribed to a change taking place in the calorific capacity of the metal; and he therefore concluded that the motion of the borer was communicated to the particles of metal, thus producing the phenomena of heat:—"It appears to me," he remarks, "extremely difficult, if not quite impossible, to form any distinct idea of anything, capable of being excited and communicated, in the manner the heat was excited and communicated in these experiments, except it be motion†."

One of the most important parts of Count RUMFORD's paper, though one to which

* Crawford on Animal Heat, p. 15.

† "An Inquiry concerning the Source of the Heat which is excited by Friction." Phil. Trans. Abridged, vol. xviii. p. 286.

little attention has hitherto been paid, is that in which he makes an estimate of the quantity of mechanical force required to produce a certain amount of heat. Referring to his third experiment, he remarks that the "total quantity of ice-cold water which, with the heat actually generated by friction, and accumulated in $2^h\ 30^m$, might have been heated 180°, or made to boil,=26·58 lbs."* In the next page he states that "the machinery used in the experiment could easily be carried round by the force of one horse (though, to render the work lighter, two horses were actually employed in doing it)." Now the power of a horse is estimated by WATT at 33,000 foot-pounds per minute, and therefore if continued for two hours and a half will amount to 4,950,000 foot-pounds, which, according to Count RUMFORD's experiment, will be equivalent to 26·58 lbs. of water raised 180°. Hence the heat required to raise a lb. of water 1° will be equivalent to the force represented by 1034 foot-pounds. This result is not very widely different from that which I have deduced from my own experiments related in this paper, viz. 772 foot-pounds; and it must be observed that the excess of Count RUMFORD's equivalent is just such as might have been anticipated from the circumstance, which he himself mentions, that "no estimate was made of the heat accumulated in the wooden box, nor of that dispersed during the experiment."

About the end of the last century Sir HUMPHRY DAVY communicated a paper to Dr. BEDDOES' West Country Contributions, entitled, "Researches on Heat, Light and Respiration," in which he gave ample confirmation to the views of Count RUMFORD. By rubbing two pieces of ice against one another in the vacuum of an air-pump, part of them was melted, although the temperature of the receiver was kept below the freezing-point. This experiment was the more decisively in favour of the doctrine of the immateriality of heat, inasmuch as the capacity of ice for heat is much less than that of water. It was therefore with good reason that DAVY drew the inference that "the immediate cause of the phenomena of heat is motion, and the laws of its communication are precisely the same as the laws of the communication of motion†."

The researches of DULONG on the specific heat of elastic fluids were rewarded by the discovery of the remarkable fact that "equal volumes of all the elastic fluids, taken at the same temperature, and under the same pressure, being compressed or dilated suddenly to the same fraction of their volume, disengage or absorb the same *absolute quantity of heat*‡." This law is of the utmost importance in the development of the theory of heat, inasmuch as it proves that the calorific effect is, under certain conditions, proportional to the force expended.

In 1834 Dr. FARADAY demonstrated the "Identity of the Chemical and Electrical Forces." This law, along with others subsequently discovered by that great man, showing the relations which subsist between magnetism, electricity and light, have

* "An Inquiry concerning the Source of the Heat which is excited by Friction." Phil. Trans. Abridged, vol. xviii. p. 283.

† Elements of Chemical Philosophy, p. 94.

‡ Mémoires de l'Académie des Sciences, t. x. p. 188.

enabled him to advance the idea that the so-called imponderable bodies are merely the exponents of different forms of Force. Mr. Grove and M. Mayer have also given their powerful advocacy to similar views.

My own experiments in reference to the subject were commenced in 1840, in which year I communicated to the Royal Society my discovery of the law of the heat evolved by voltaic electricity, a law from which the immediate deductions were drawn,—1st, that the heat evolved by any voltaic pair is proportional, *cœteris paribus*, to its intensity or electromotive force*; and 2nd, that the heat evolved by the combustion of a body is proportional to the intensity of its affinity for oxygen†. I thus succeeded in establishing relations between heat and chemical affinity. In 1843 I showed that the heat evolved by magneto-electricity is proportional to the force absorbed; and that the force of the electro-magnetic engine is derived from the force of chemical affinity in the battery, a force which otherwise would be evolved in the form of heat: from these facts I considered myself justified in announcing "that the quantity of heat capable of increasing the temperature of a lb. of water by one degree of Fahrenheit's scale, is equal to, and may be converted into, a mechanical force capable of raising 838 lbs. to the perpendicular height of one foot‡."

In a subsequent paper, read before the Royal Society in 1844, I endeavoured to show that the heat absorbed and evolved by the rarefaction and condensation of air is proportional to the force evolved and absorbed in those operations§. The quantitative relation between force and heat deduced from these experiments, is almost identical with that derived from the electro-magnetic experiments just referred to, and is confirmed by the experiments of M. Seguin on the dilatation of steam‖.

From the explanation given by Count Rumford of the heat arising from the friction of solids, one might have anticipated, as a matter of course, that the evolution of heat would also be detected in the friction of liquid and gaseous bodies. Moreover there were many facts, such as, for instance, the warmth of the sea after a few days of stormy weather, which had long been commonly attributed to fluid friction. Nevertheless the scientific world, preoccupied with the hypothesis that heat is a substance, and following the deductions drawn by Pictet from experiments not sufficiently delicate, have almost unanimously denied the possibility of generating heat in that way. The first mention, so far as I am aware, of experiments in which the evolution of heat from fluid friction is asserted, was in 1842 by M. Mayer¶, who states that he has raised the temperature of water from 12° C. to 13° C., by agitating it, without however indicating the quantity of force employed, or the precautions taken to secure a correct result. In 1843 I announced the fact that "heat is evolved by the passage of water through narrow tubes**," and that each degree of heat per lb. of water required for its evolution in this way a mechanical force represented by

* Phil. Mag. vol. xix. p. 275. † Ibid. vol. xx. p. 111. ‡ Ibid. vol. xxiii. p. 441.

§ Ibid. vol. xxvi. pp. 375. 379. ‖ Comptes Rendus, t. 25, p. 421.

¶ Annalen of Wœhler and Liebig, May 1842. ** Phil. Mag. vol. xxiii. p. 442.

770 foot-pounds. Subsequently, in 1845* and 1847†, I employed a paddle-wheel to produce the fluid friction, and obtained the equivalents 781·5, 782·1 and 787·6, respectively, from the agitation of water, sperm-oil and mercury. Results so closely coinciding with one another, and with those previously derived from experiments with elastic fluids and the electro-magnetic machine, left no doubt on my mind as to the existence of an equivalent relation between force and heat; but still it appeared of the highest importance to obtain that relation with still greater accuracy. This I have attempted in the present paper.

Description of Apparatus.—The thermometers employed had their tubes calibrated and graduated according to the method first indicated by M. REGNAULT. Two of them, which I shall designate by A and B, were constructed by Mr. DANCER of Manchester; the third, designated by C, was made by M. FASTRÉ of Paris. The graduation of these instruments was so correct, that when compared together their indications coincided to about $\frac{1}{100}$th of a degree FAHR. I also possessed another exact instrument made by Mr. DANCER, the scale of which embraced both the freezing and boiling-points. The latter point in this standard thermometer was obtained, in the usual manner, by immersing the bulb and stem in the steam arising from a considerable quantity of pure water in rapid ebullition. During the trial the barometer stood at 29·94 inches, and the temperature of the air was 50°; so that the observed point required very little correction to reduce it to 0·760 metre and 0° C., the pressure used in France, and I believe the Continent generally, for determining the boiling-point, and which has been employed by me on account of the number of accurate thermometrical researches which have been constructed on that basis‡. The values of the scales of thermometers A and B were ascertained by plunging them along with the standard in large volumes of water kept constantly at various temperatures. The value of the scale of thermometer C was determined by comparison with A. It was thus found that the number of divisions corresponding to 1° FAHR. in the thermometers A, B and C, were 12·951, 9·829 and 11·647, respectively. And since constant practice had enabled me to read off with the naked eye to $\frac{1}{20}$th of a division, it followed that $\frac{1}{200}$th of a degree FAHR. was an appreciable temperature.

Plate VII. fig. 1 represents a vertical, and fig. 2 a horizontal plan of the apparatus employed for producing the friction of water, consisting of a brass paddle-wheel furnished with eight sets of revolving arms, *a*, *a*, &c., working between four sets of stationary vanes,

* Phil. Mag., vol. xxvii. p. 205. † Ibid. vol. xxxi. p. 173, and Comptes Rendus, tome xxv. p. 309.

‡ A barometrical pressure of 30 inches of mercury at 60° is very generally employed in this country, and fortunately agrees almost exactly with the continental standard. In the "Report of the Committee appointed by the Royal Society to consider the best method of adjusting the Fixed Points of Thermometers," Philosophical Transactions, Abridged, xiv. p. 258, the barometrical pressure 29·8 is recommended, but the temperature is not named,—a remarkable omission in a work so exact in other respects.

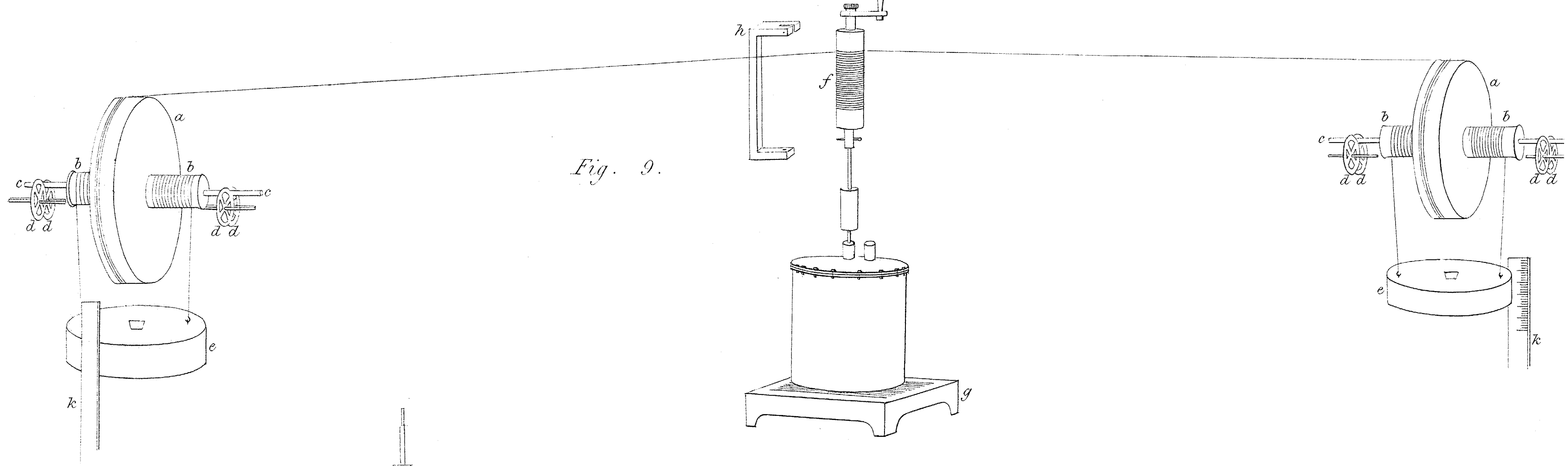


Fig. 9.

Fig. 2.

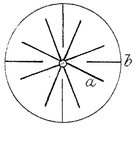


Fig. 1.

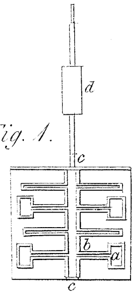


Fig. 3. a b

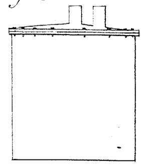
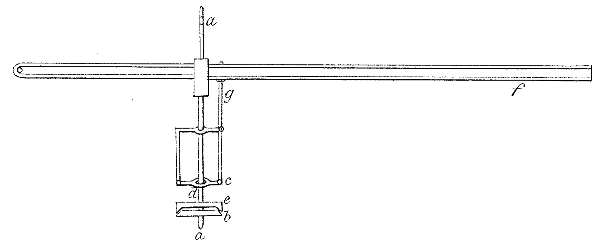


Fig. 7.



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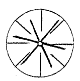

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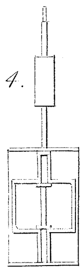

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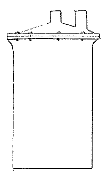
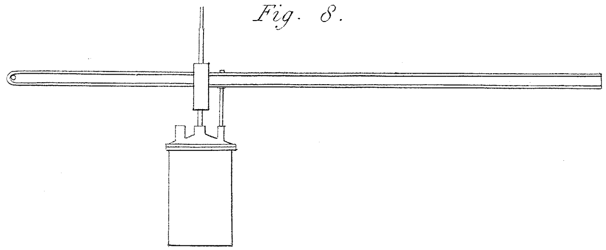


Fig. 8.



Scale One Inch to a Foot.

Mr. Joule on the Mechanical Equivalent of Heat.

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b, *b*, &c., affixed to a framework also in sheet brass. The brass axis of the paddle-wheel worked freely, but without shaking, on its bearings at *c*, *c*, and at *d* was divided into two parts by a piece of boxwood intervening, so as to prevent the conduction of heat in that direction.

Fig. 3 represents the copper vessel into which the revolving apparatus was firmly fitted: it had a copper lid, the flange of which, furnished with a very thin washer of leather saturated with white-lead, could be screwed perfectly water-tight to the flange of the copper vessel. In the lid there were two necks, *a*, *b*, the former for the axis to revolve in without touching, the latter for the insertion of the thermometer.

Besides the above I had a similar apparatus for experiments on the friction of mercury, which is represented by figs. 4, 5 and 6. It differed from the apparatus already described in its size; number of vanes, of which six were rotary and eight sets stationary; and material, which was wrought iron in the paddle-wheel, and cast iron in the vessel and lid.

Being anxious to extend my experiments to the friction of solids, I also procured the apparatus represented by fig. 7, in which *a a* is the axis revolving along with the beveled cast-iron wheel *b*, the rim of which was turned true. By means of the lever *c*, which had a ring in its centre for the axis to pass through, and two short arms *d*, the bevel turned cast-iron wheel *e* could be pressed against the revolving wheel; the degree of force applied being regulated by hand by means of the wooden lever *f* attached to the perpendicular iron rod *g*. Fig. 8 represents the apparatus in its cast-iron vessel.

Fig. 9 is a perspective view of the machinery employed to set the frictional apparatus just described in motion. *a a* are wooden pulleys, 1 foot in diameter and 2 inches thick, having wooden rollers *bb*, *bb*, 2 inches in diameter, and steel axles *cc*, *cc*, one quarter of an inch in diameter. The pulleys were turned perfectly true and equal to one another. Their axles were supported by brass friction wheels *dddd*, *dddd*, the steel axles of which worked in holes drilled into brass plates attached to a very strong wooden framework firmly fixed into the walls of the apartment*.

The leaden weights *e*, *e*, which in some of the ensuing experiments weighed about 29 lbs., and in others about 10 lbs. a piece, were suspended by string from the rollers *bb*, *b b*; and fine twine attached to the pulleys *a a*, connected them with the central roller *f*, which, by means of a pin, could with facility be attached to, or removed from, the axis of the frictional apparatus.

The wooden stool *g*, upon which the frictional apparatus stood, was perforated by a number of transverse slits, so cut out that only a very few points of wood came in contact with the metal, whilst the air had free access to almost every part of it. In this way the conduction of heat to the substance of the stool was avoided.

* This was a spacious cellar, which had the advantage of possessing an uniformity of temperature far superior to that of any other laboratory I could have used.

A large wooden screen (not represented in the figure) completely obviated the effects of radiant heat from the person of the experimenter.

The method of experimenting was simply as follows :—The temperature of the frictional apparatus having been ascertained and the weights wound up with the assistance of the stand *h*, the roller was refixed to the axis. The precise height of the weights above the ground having then been determined by means of the graduated slips of wood *k*, *k*, the roller was set at liberty and allowed to revolve until the weights reached the flagged floor of the laboratory, after accomplishing a fall of about 63 inches. The roller was then removed to the stand, the weights wound up again, and the friction renewed. After this had been repeated twenty times, the experiment was concluded with another observation of the temperature of the apparatus. The mean temperature of the laboratory was determined by observations made at the commencement, middle and termination of each experiment.

Previously to, or immediately after each of the experiments, I made trial of the effect of radiation and conduction of heat to or from the atmosphere, in depressing or raising the temperature of the frictional apparatus. In these trials, the position of the apparatus, the quantity of water contained by it, the time occupied, the method of observing the thermometers, the position of the experimenter, in short everything, with the exception of the apparatus being at rest, was the same as in the experiments in which the effect of friction was observed.

1*st Series of Experiments*.—Friction of Water. Weight of the leaden weights along with as much of the string in connexion with them as served to increase the pressure, 203066 grs. and 203086 grs. Velocity of the weights in descending, 2·42 inches per second. Time occupied by each experiment, 35 minutes. Thermometer employed for ascertaining the temperature of the water, A. Thermometer for registering the temperature of the air, B.

TABLE I.

No. of experiment and cause of change of temperature.	Total fall of weights in inches.	Mean temperature of air.	Difference between mean of columns 5 and 6 and column 3.	Temperature of apparatus.		Gain or loss of heat during experiment.
				Commencement of experiment.	Termination of experiment.	
1 Friction	1256·96	57°·698	2°·252 −	55°·118	55°·774	0°·656 gain
1 Radiation ...	0	57·868	2·040 −	55·774	55·882	0·108 gain
2 Friction	1255·16	58·085	1·875 −	55·882	56·539	0·657 gain
2 Radiation ...	0	58·370	1·789 −	56·539	56·624	0·085 gain
3 Friction	1253·66	60·788	1·596 −	58·870	59·515	0·645 gain
3 Radiation ...	0	60·926	1·373 −	59·515	59·592	0·077 gain
4 Friction	1252·74	61·001	1·110 −	59·592	60·191	0·599 gain
4 Radiation ...	0	60·890	0·684 −	60·191	60·222	0·031 gain
1	2	3	4	5	6	7

TABLE I. (Continued.)

No. of experiment and cause of change of temperature.	Total fall of weights in inches.	Mean temperature of air.	Difference between mean of columns 5 and 6 and column 3.	Temperature of apparatus. Commencement of experiment.	Temperature of apparatus. Termination of experiment.	Gain or loss of heat during experiment.
5 Friction......	1251·81	60°·940	0°·431−	60°·222	60°·797	0°·575 gain
5 Radiation ...	0	61·035	0·237−	60·797	60·799	0·002 gain
6 Radiation ...	0	59·675	0·125+	59·805	59·795	0·010 loss
6 Friction ...	1254·71	59·919	0·157+	59·795	60·357	0·562 gain
7 Radiation ...	0	59·888	0·209−	59·677	59·681	0·004 gain
7 Friction......	1254·02	60·076	0·111−	59·681	60·249	0·568 gain
8 Radiation ...	0	58·240	0·609+	58·871	58·828	0·043 loss
8 Friction......	1251·22	58·237	0·842+	58·828	59·330	0·502 gain
9 Friction......	1253·92	55·328	0·070+	55·118	55·678	0·560 gain
9 Radiation ...	0	55·528	0·148+	55·678	55·674	0·004 loss
10 Radiation ...	0	54·941	0·324−	54·614	54·620	0·006 gain
10 Friction......	1257·96	54·985	0·085−	54·620	55·180	0·560 gain
11 Radiation ...	0	55·111	0·069+	55·180	55·180	0·000
11 Friction......	1258·59	55·229	0·227+	55·180	55·733	0·553 gain
12 Friction......	1258·71	55·433	0·238+	55·388	55·954	0·566 gain
12 Radiation ...	0	55·687	0·265+	55·954	55·950	0·004 loss
13 Friction......	1257·91	55·677	0·542+	55·950	56·488	0·538 gain
13 Radiation ...	0	55·674	0·800+	56·488	56·461	0·027 loss
14 Radiation ...	0	55·579	0·583−	54·987	55·006	0·019 gain
14 Friction......	1259·69	55·864	0·568−	55·006	55·587	0·581 gain
15 Radiation ...	0	56·047	0·448−	55·587	55·612	0·025 gain
15 Friction......	1259·89	56·182	0·279−	55·612	56·195	0·583 gain
16 Friction......	1259·64	55·368	0·099+	55·195	55·739	0·544 gain
16 Radiation ...	0	55·483	0·250+	55·739	55·728	0·011 loss
17 Friction......	1259·64	55·498	0·499+	55·728	56·266	0·538 gain
17 Radiation ...	0	55·541	0·709+	56·266	56·235	0·031 loss
18 Radiation ...	0	56·769	1·512−	55·230	55·284	0·054 gain
18 Friction......	1260·17	56·966	1·372−	55·284	55·905	0·621 gain
19 Radiation ...	0	60·058	1·763−	58·257	58·334	0·077 gain
19 Friction......	1262·24	60·112	1·450−	58·334	58·990	0·656 gain
20 Radiation ...	0	60·567	1·542−	58·990	59·060	0·070 gain
20 Friction......	1261·94	60·611	1·239−	59·060	59·685	0·625 gain
21 Friction......	1264·07	58·654	0·321−	58·050	58·616	0·566 gain
21 Radiation ...	0	58·627	0·018−	58·616	58·603	0·013 loss
22 Friction......	1262·97	58·631	0·243+	58·603	59·145	0·542 gain
22 Radiation ...	0	58·624	0·505+	59·145	59·114	0·031 loss
23 Friction......	1264·72	59·689	1·100−	58·284	58·894	0·610 gain
23 Radiation ...	0	59·943	1·027−	58·894	58·938	0·044 gain
1	2	3	4	5	6	7

TABLE I. (Continued.)

No. of experiment and cause of change of temperature.	Total fall of weights in inches.	Mean temperature of air.	Difference between mean of columns 5 and 6 and column 3.	Temperature of apparatus. Commencement of experiment.	Temperature of apparatus. Termination of experiment.	Gain or loss of heat during experiment.
24 Radiation ...	0	60·157	1·160 –	58·977	59·017	0·040 gain
24 Friction	1263·94	59·811	0·505 –	59·017	59·595	0·578 gain
25 Radiation ...	0	59·654	0·061 –	59·595	59·591	0·004 loss
25 Friction	1263·49	59·675	0·185 +	59·591	60·129	0·538 gain
26 Radiation ...	0	59·156	0·609 –	58·541	58·554	0·013 gain
26 Friction	1263·49	59·333	0·488 –	58·554	59·137	0·583 gain
27 Friction	1263·99	59·536	0·198 –	59·054	59·623	0·569 gain
27 Radiation ...	0	59·726	0·101 –	59·623	59·627	0·004 gain
28 Friction	1263·99	59·750	0·155 +	59·627	60·183	0·556 gain
28 Radiation ...	0	59·475	0·102 +	59·585	59·569	0·016 loss
29 Friction	1263·31	58·695	0·182 –	58·230	58·796	0·566 gain
29 Radiation ...	0	58·906	0·108 –	58·796	58·801	0·005 gain
30 Radiation ...	0	59·770	1·286 –	58·454	58·515	0·061 gain
30 Friction	1263·99	60·048	1·223 –	58·515	59·135	0·620 gain
31 Friction	1263·49	59·343	0·022 +	59·091	59·639	0·548 gain
31 Radiation ...	0	59·435	0·198 +	59·639	59·627	0·012 loss
32 Radiation ...	0	59·374	0·357 –	59·015	59·020	0·005 gain
32 Friction	1263·49	59·407	0·105 –	59·020	59·585	0·565 gain
33 Radiation ...	0	59·069	0·201 –	58·867	58·870	0·003 gain
33 Friction	1263·49	59·234	0·081 –	58·870	59·436	0·566 gain
34 Friction	1262·99	56·328	0·331 +	56·387	56·932	0·545 gain
34 Radiation ...	0	56·643	0·287 +	56·932	56·929	0·003 loss
35 Friction	1262·99	56·790	0·413 +	56·929	57·477	0·548 gain
35 Radiation ...	0	56·772	0·687 +	57·477	57·442	0·035 loss
36 Radiation ...	0	55·839	0·304 –	55·527	55·543	0·016 gain
36 Friction	1262·99	56·114	0·281 –	55·543	56·124	0·581 gain
37 Radiation ...	0	56·257	0·127 –	56·124	56·137	0·013 gain
37 Friction	1262·99	56·399	0·024 +	56·137	56·709	0·572 gain
38 Radiation ...	0	55·826	0·065 –	55·759	55·764	0·005 gain
38 Friction	1262·99	55·951	0·093 +	55·764	56·325	0·561 gain
39 Radiation ...	0	56·101	0·220 +	56·325	56·317	0·008 loss
39 Friction	1262·99	56·182	0·409 +	56·317	56·865	0·548 gain
40 Friction	1262·99	56·108	0·100 +	55·929	56·488	0·559 gain
40 Radiation ...	0	56·454	0·036 +	56·488	56·492	0·004 gain
Mean Friction...	1260·248	....	0·305075 –	....	....	0·575250 gain
Mean Radiation.	0	....	0·322950 –	....	....	0·012975 gain
1	2	3	4	5	6	7

From the various experiments in the above Table in which the effect of radiation was observed, it may be readily gathered that the effect of the temperature of the surrounding air upon the apparatus was, for each degree of difference between the mean temperature of the air and that of the apparatus, $0^{\circ}\cdot04654$. Therefore, since the excess of the temperature of the atmosphere over that of the apparatus was $0^{\circ}\cdot32295$ in the mean of the radiation experiments, but only $0^{\circ}\cdot305075$ in the mean of the friction experiments, it follows that $0^{\circ}\cdot000832$ must be added to the difference between $0^{\circ}\cdot57525$ and $0^{\circ}\cdot012975$, and the result, $0^{\circ}\cdot563107$, will be the proximate heating effect of the friction. But to this quantity a small correction must be applied on account of the mean of the temperatures of the apparatus at the commencement and termination of each friction experiment having been taken for the true mean temperature, which was not strictly the case, owing to the somewhat less rapid increase of temperature towards the termination of the experiment when the water had become warmer. The mean temperature of the apparatus in the friction experiments ought therefore to be estimated $0^{\circ}\cdot002184$ higher, which will diminish the heating effect of the atmosphere by $0^{\circ}\cdot000102$. This, added to $0^{\circ}\cdot563107$, gives $0^{\circ}\cdot563209$ as the true mean increase of temperature due to the friction of water*.

In order to ascertain the absolute quantity of heat evolved, it was necessary to find the capacity for heat of the copper vessel and brass paddle-wheel. That of the former was easily deduced from the specific heat of copper according to M. Regnault. Thus, capacity of 25541 grs.† of copper $\times 0\cdot09515 =$ capacity of 2430·2 grs. of water. A series of seven very careful experiments with the brass paddle-wheel gave me 1783 grs. of water as its capacity, after making all the requisite corrections for the heat occasioned by the contact of the water with the surface of the metal, &c. But on account of the magnitude of these corrections, amounting to one-thirtieth of the whole capacity, I prefer to avail myself of M. Regnault's law, viz. *that the capacity in metallic alloys is equal to the sum of the capacities of their constituent metals*‡. Analysis of a part of the wheel proved it to consist of a very pure brass containing 3933 grs. of zinc. to 14968 grs. of copper. Hence

Cap. 14968 grs. copper $\times 0\cdot09515 =$ cap. 1424·2 grs. water.
Cap. 3933 grs. zinc $\times 0\cdot09555 =$ cap. 375·8 grs. water.

Total cap. brass wheel = cap. 1800 grs. water.

* This increase of temperature was, it is necessary to observe, a mixed quantity, depending partly upon the friction of the water, and partly upon the friction of the vertical axis of the apparatus upon its pivot and bearing, *c c*, fig. 1. The latter source of heat was however only equal to about $\frac{1}{80}$th of the former. Similarly also, in the experiments on the friction of solids hereafter detailed, the cast-iron discs revolving in mercury, rendered it impossible to avoid a very small degree of friction among the particles of that fluid. But since it was found that the quantity of heat evolved was the same, for the same quantity of force expended, in both cases, *i. e.* whether a minute quantity of heat arising from friction of solids was mixed with the heat arising from the friction of a fluid, or whether, on the other hand, a minute quantity of heat arising from the friction of a fluid was mingled with the heat developed by the friction of solids, I thought there could be no impropriety in considering the heat as if developed from a simple source,—in the one case entirely from the friction of a fluid, and in the other entirely from the friction of a solid body.

† The washer, weighing only 38 grs., was reckoned as copper in this estimate.

‡ Ann. de Ch. 1841, t. i.

The capacity of a brass stopper which was placed in the neck *b*, fig. 3, for the purpose of preventing the contact of air with the water as much as possible, was equal to that of 10·3 grs. of water: the capacity of the thermometer had not to be estimated, because it was always brought to the expected temperature before immersion. The entire capacity of the apparatus was therefore as follows:—

Water	93229·7
Copper as water. . .	2430·2
Brass as water . . .	1810·3
Total . .	97470·2

So that the total quantity of heat evolved was 0°·563209 in 97470·2 grs. of water, or, in other words, 1° FAHR. in 7·842299 lbs. of water.

The estimate of the force applied in generating this heat may be made as follows: —The weights amounted to 406152 grs., from which must be subtracted the friction arising from the pulleys and the rigidity of the string; which was found by connecting the two pulleys with twine passing round a roller of equal diameter to that employed in the experiments. Under these circumstances, the weight required to be added to one of the leaden weights in order to maintain them in equable motion was found to be 2955 grs. The same result, in the opposite direction, was obtained by adding 3055 grs. to the other leaden weight. Deducting 168 grs., the friction of the roller on its pivots, from 3005, the mean of the above numbers, we have 2837 grs. as the amount of friction in the experiments, which, subtracted from the leaden weights, leaves 403315 grs. as the actual pressure applied.

The velocity with which the leaden weights came to the ground, viz. 2·42 inches per second, is equivalent to an altitude of 0·0076 inch. This, multiplied by 20, the number of times the weights were wound up in each experiment, produces 0·152 inch, which, subtracted from 1260·248, leaves 1260·096 as the corrected mean height from which the weights fell.

This fall, accompanied by the above-mentioned pressure, represents a force equivalent to 6050·186 lbs. through one foot; and $0·8464 \times 20 = 16·928$ foot-lbs. added to it, for the force developed by the elasticity of the string after the weights had touched the ground, gives 6067·114 foot-pounds as the mean corrected force.

Hence $\frac{6067·114}{7·842299} = 773·64$ foot-pounds, will be the force which, according to the above experiments on the friction of water, is equivalent to 1° FAHR. in a lb. of water.

2nd Series of Experiments.—Friction of Mercury. Weight of the leaden weights and string, 203026 grs. and 203073 grs. Velocity of the weights in descending, 2·43 inches per second. Time occupied by each experiment, 30 minutes. Thermometer for ascertaining the temperature of the mercury, C. Thermometer for registering the temperature of the air, B. Weight of cast iron apparatus, 68446 grs. Weight of mercury contained by it, 428292 grs.

Table II.

No. of experiment and cause of change of temperature.	Total fall of weights in inches.	Mean temperature of air.	Difference between mean of columns 5 and 6 and column 3.	Temperature of apparatus.		Gain or loss of heat during experiment.
				Commencement of experiment.	Termination of experiment.	
1 Friction......	1265·42	58°·491	1°·452 +	58°·780	61°·107	2°·327 gain
1 Radiation ...	0	58·939	2·056 +	61·107	60·884	0·223 loss
2 Radiation ...	0	58·390	0·237 –	58·119	58·188	0·069 gain
2 Friction......	1265·77	58·949	0·467 +	58·188	60·644	2·456 gain
3 Friction......	1265·73	57·322	1·203 +	57·325	59·725	2·400 gain
3 Radiation ...	0	57·942	1·678 +	59·725	59·515	0·210 loss
4 Radiation ...	0	57·545	0·010 –	57·518	57·553	0·035 gain
4 Friction......	1264·72	58·135	0·624 +	57·553	59·965	2·412 gain
5 Friction......	1265·73	57·021	0·907 +	56·715	59·141	2·426 gain
5 Radiation ...	0	57·596	1·474 +	59·141	58·999	0·142 loss
6 Radiation ...	0	56·406	0·174 +	56·565	56·595	0·030 gain
6 Friction......	1265·65	57·057	0·749 +	56·595	59·017	2·422 gain
7 Friction......	1269·55	58·319	0·049 +	57·115	59·622	2·507 gain
7 Radiation ...	0	58·771	0·831 +	59·622	59·583	0·039 loss
8 Radiation ...	0	60·363	0·612 –	59·691	59·811	0·120 gain
8 Friction......	1257·70	60·842	0·209 +	59·811	62·292	2·481 gain
9 Friction......	1255·77	60·282	1·044 +	60·129	62·524	2·395 gain
9 Radiation ...	0	60·862	1·576 +	62·524	62·352	0·172 loss
10 Friction......	1255·33	60·725	0·764 +	60·266	62·713	2·447 gain
10 Radiation ...	0	61·340	1·313 +	62·713	62·593	0·120 loss
11 Radiation ...	0	58·654	0·109 +	58·755	58·772	0·017 gain
11 Friction......	1266·47	59·234	0·746 +	58·772	61·189	2·417 gain
12 Radiation ...	0	56·436	0·247 +	56·673	56·694	0·021 gain
12 Friction......	1265·80	57·240	0·673 +	56·694	59·133	2·439 gain
13 Friction......	1264·70	55·002	1·808 +	55·638	57·982	2·344 gain
13 Radiation ...	0	55·633	2·213 +	57·982	57·711	0·271 loss
14 Friction......	1265·20	54·219	1·273 +	54·290	56·694	2·404 gain
14 Radiation ...	0	54·595	1·972 +	56·694	56·441	0·253 loss
15 Radiation ...	0	53·476	0·174 +	53·633	53·667	0·034 gain
15 Friction......	1265·63	53·995	0·872 +	53·667	56·067	2·400 gain
16 Radiation ...	0	52·082	0·254 +	52·332	52·341	0·009 gain
16 Friction......	1265·45	52·479	1·047 +	52·341	54·711	2·370 gain
17 Friction......	1257·50	50·485	1·453 +	50·772	53·105	2·333 gain
17 Radiation ...	0	50·821	2·164 +	53·105	52·865	0·240 loss
18 Radiation ...	0	48·944	0·450 –	48·434	48·554	0·120 gain
18 Friction......	1257·50	49·330	0·462 +	48·554	51·031	2·477 gain
19 Friction......	1257·50	48·135	1·273 +	48·219	50·598	2·379 gain
19 Radiation ...	0	48·725	1·780 +	50·598	50·413	0·185 loss
20 Radiation ...	0	48·878	0·148 –	48·687	48·773	0·086 gain
20 Friction......	1257·50	49·397	0·597 +	48·773	51·216	2·443 gain
Mean Friction	1262·731	....	0·8836+	....	....	2·41395 gain
Mean Radiation	0	....	0·8279+	....	....	0·06570 loss
1	2	3	4	5	6	7

From the above Table, it appears that the effect of each degree of difference between the temperature of the laboratory and that of the apparatus was 0°·13742. Hence 2°·41395+0°·0657+0°·007654=2°·487304, will be the proximate value of the increase of temperature in the experiments. The further correction on account of the mean temperature of the apparatus in the friction experiments having been in reality 0°·028484 higher than is indicated by the table, will be 0°·003914, which, added to the proximate result, gives 2°·491218 as the true thermometrical effect of the friction of the mercury.

In order to obtain the absolute quantity of heat evolved, it was requisite to ascertain the capacity for heat of the apparatus. I therefore caused it to be suspended by iron wire from a lever so contrived that the apparatus could be moved with rapidity and ease to any required position. The temperature of the apparatus having then been raised about 20°, it was placed in a warm air-bath, in order to keep its temperature uniform for a quarter of an hour, during which time the thermometer C, immersed in the mercury, was from time to time observed. The apparatus was then rapidly immersed into a thin copper vessel containing 141826 grs. of distilled water, the temperature of which was repeatedly observed by thermometer A. During the experiment the water was repeatedly agitated by a copper stirrer; and every precaution was taken to keep the surrounding atmosphere in a uniform state, and also to prevent the disturbing effects of radiation from the person of the experimenter. In this way I obtained the following results:—

	Time of observation.	Temperature of water.	Temperature of apparatus.
	′	°	°
Apparatus in air-bath	0	47·705	70·518
	5	47·705	70·492
	10	47·713	70·518
Instant of immersion	11		
Apparatus immersed in water	13½	49·836	57·673
	16	50·493	52·641
	21	50·694	50·941
	26	50·690	50·778
	31	50·667	50·744
	36	50·636	50·709

By applying the correction to the temperature of the water due to its observed increase during the first ten minutes of the experiment, and the still smaller correction due to the rise of the water in the can covering 60 square inches of copper at the temperature of the atmosphere, 47°·714 was found to be the temperature of the water at the instant of immersion. To remove the apparatus from the warm air-bath, and to immerse it into the water, occupied only 10″, during which it must (according to preliminary experiments) have cooled 0°·027. The heating effect of the air-bath

during the remaining 50″ (estimated from the rate of increase of temperature between the observations at 5′ and 10′) will be 0°·004. These corrections, applied to 70°·518, leave 70°·495 as the temperature of the apparatus at the moment of immersion.

The temperature of the apparatus at 26′ was 50°·778, indicating a loss of 19°·717. That of the water at the same time of observation, being corrected for the effect of the atmosphere (deduced from the observations of the cooling from 26′ to 36′ and of the heating from 0′ to 10′), will be 50°·777, indicating a gain of 3°·063. Twenty such results, obtained in exactly the same manner, are collected in the following Table.

TABLE III.

No.	Corrected temperature of water. Commencement of experiment.	Corrected temperature of water. Termination of experiment.	Gain of heat by the water.	Corrected temperature of apparatus. Commencement of experiment.	Corrected temperature of apparatus. Termination of experiment.	Loss of heat by the apparatus.
1	47°·714	50°·777	3°·063	70°·495	50°·778	19°·717
2	48·127	51·113	2·986	70·518	51·147	19·371
3	48·453	51·430	2·977	70·642	51·452	19·190
4	47·543	50·598	3·055	70·674	50·684	19·990
5	44·981	48·449	3·468	70·901	48·468	22·433
6	45·289	48·701	3·412	70·769	48·657	22·112
7	45·087	48·497	3·410	70·504	48·494	22·010
8	46·375	49·614	3·239	70·678	49·662	21·016
9	47·671	50·832	3·161	71·500	50·873	20·627
10	47·693	50·801	3·108	70·878	50·821	20·057
11	48·728	51·714	2·986	70·947	51·714	19·233
12	47·240	50·414	3·174	71·006	50·392	20·614
13	48·324	51·345	3·021	70·939	51·362	19·577
14	49·079	51·905	2·826	70·332	51·937	18·395
15	49·635	52·490	2·855	71·012	52·504	18·508
16	47·207	50·282	3·075	70·265	50·263	20·002
17	46·227	49·402	3·175	69·877	49·314	20·563
18	46·053	49·296	3·243	70·367	49·258	21·109
19	45·733	48·981	3·248	70·068	49·001	21·067
20	47·170	50·317	3·147	70·741	50·332	20·409
Mean...	....	....	3·13145	....	....	20·300

I did not consider these experiments on the capacity of the apparatus sufficiently complete, until I had ascertained the heat produced by the wetting of the surface of the iron vessel. For this purpose the following trials were made in a similar manner to the above, with the exception that the observations did not require to be extended beyond 26′.

TABLE IV.

No.	Corrected temperature of water. Commencement of experiment.	Corrected temperature of water. Termination of experiment.	Gain or loss of heat by water.	Corrected temperature of apparatus. Commencement of experiment.	Corrected temperature of apparatus. Termination of experiment.	Gain or loss of heat by apparatus.
1	50°·558	50°·556	0°·002 loss	50°·565	50°·589	0°·024 gain
2	49·228	49·232	0·004 gain	49·239	49·254	0·015 gain
3	48·095	48·106	0·011 gain	48·034	48·099	0·065 gain
4	47·416	47·425	0·009 gain	47·384	47·429	0·045 gain
5	47·484	47·532	0·048 gain	48·103	47·782	0·321 loss
6	47·429	47·439	0·010 gain	47·703	47·610	0·093 loss
7	47·624	47·637	0·013 gain	47·870	47·790	0·080 loss
8	47·705	47·712	0·007 gain	47·915	47·859	0·056 loss
9	47·685	47·702	0·017 gain	47·891	47·837	0·054 loss
10	48·733	48·793	0·060 gain	49·498	49·112	0·386 loss
11	49·689	49·694	0·005 gain	49·946	49·842	0·104 loss
12	48·191	48·168	0·023 loss	47·972	48·134	0·162 gain
13	48·101	48·119	0·018 gain	48·310	48·254	0·056 loss
14	49·413	49·390	0·023 loss	49·249	49·413	0·164 gain
15	49·243	49·241	0·002 loss	49·343	49·318	0·025 loss
16	49·103	49·103	0	49·172	49·172	0
17	46·991	46·902	0·089 loss	46·204	46·923	0·719 gain
18	46·801	46·814	0·013 gain	47·139	46·953	0·186 loss
19	46·624	46·624	0	46·652	46·652	0
20	46·266	46·158	0·108 loss	45·369	46·167	0·798 gain
Mean...	....	....	0·0016 loss	....	....	0·03155 gain

By adding these results to those of the former table, we have a gain of temperature in the water of 3°·13305, and a loss in the apparatus of 20°·33155. Now the capacity of the can of water was estimated as follows:—

Water	141826 grs.
15622 grs. copper as water . .	1486 grs.
Thermometer and stirrer as water	118 grs.
Total	143430 grs.

Hence $\frac{3\cdot13305}{20\cdot33155}\times 143430 = 22102\cdot27$, the capacity of the apparatus as tried. The addition of 21·41 (the capacity of 643 grs. of mercury which had been removed in order to admit of the expansion of 70°) to, and the substraction of 52 grs. (the capacity of the bulb of thermometer C, and of the iron wire employed in suspending the apparatus) from this result, leaves 22071·68 grs. of water as the capacity of the apparatus employed in the friction of mercury.

The temperature 2°·491218 in the above capacity, equivalent to 1° in 7·85505 lbs. of water, was therefore the absolute mean quantity of heat evolved by the friction of mercury.

The leaden weights amounted to 406099 grs., from which 2857 grs., subtracted for the friction of the pulleys, leaves 403242 grs. The mean height from which they fell, as given in Table II., was 1262·731 inches, from which 0·152 inch, subtracted for the velocity of fall, leaves 1262·579 inches. This height, combined with the above weight, is equivalent to 6061·01 foot-lbs., which, increased by 16·929 foot-lbs. on account of the elasticity of the string, gives 6077·939 foot-lbs. as the mean force employed in the experiments.

$\frac{6077·939}{7·85505}=773·762$; which is therefore the equivalent derived from the above experiments on the friction of mercury. The next series of experiments were made with the same apparatus, using lighter weights.

3rd Series of Experiments.—Friction of Mercury. Weight of the leaden weights and string, 68442 grs. and 68884 grs. Velocity of the weights in descending, 1·4 inch per second. Time occupied by each experiment, 35 minutes. Thermometer for ascertaining the temperature of the mercury, C. Thermometer for registering the temperature of the air, B.

TABLE V.

No. of experiment and cause of change of temperature.	Total fall of weights in inches.	Mean temperature of air.	Difference between mean of columns 5 and 6 and column 3.	Temperature of apparatus.		Gain or loss of heat during experiment.
				Commencement of experiment.	Termination of experiment.	
1 Friction.........	1292·12	49·539°	0·399°+	49·507°	50·370°	0·863° gain
1 Radiation	0	50·165	0·226+	50·370	50·413	0·043 gain
2 Friction.........	1292·00	49·865	0·189+	49·606	50·503	0·897 gain
2 Radiation	0	50·363	0·159+	50·503	50·542	0·039 gain
3 Friction.........	1293·18	50·139	0·460+	50·168	51·030	0·862 gain
3 Radiation	0	50·617	0·408+	51·030	51·021	0·009 loss
4 Radiation	0	50·750	0·146+	50·873	50·920	0·047 gain
4 Friction.........	1293·25	51·401	0·013—	50·920	51·856	0·936 gain
5 Radiation	0	49·936	0·121+	50·031	50·083	0·052 gain
5 Friction.........	1294·92	50·551	0·020—	50·083	50·980	0·897 gain
6 Radiation	0	50·638	0·135+	50·752	50·795	0·043 gain
6 Friction.........	1294·43	51·172	0·065+	50·795	51·680	0·885 gain
7 Radiation	0	51·553	0·260—	51·237	51·349	0·112 gain
7 Friction.........	1294·07	52·194	0·371—	51·349	52·298	0·949 gain
8 Friction.........	1293·30	52·774	0·019—	52·298	53·212	0·914 gain
8 Radiation	0	53·029	0·204+	53·212	53·255	0·043 gain
9 Friction.........	1294·05	51·513	0·306+	51·379	52·259	0·880 gain
9 Radiation	0	52·093	0·177+	52·259	52·281	0·022 gain
10 Friction.........	1293·95	51·197	0·180+	50·907	51·847	0·940 gain
10 Radiation	0	51·960	0·079—	51·847	51·916	0·069 gain
11 Friction.........	1292·80	50·577	0·652+	50·804	51·654	0·850 gain
11 Radiation	0	51·055	0·577+	51·654	51·611	0·043 loss
1	2	3	4	5	6	7

Table V. (Continued.)

No. of experiment and cause of change of temperature.	Total fall of weights in inches.	Mean temperature of air.	Difference between mean of columns 5 and 6 and column 3.	Temperature of apparatus.		Gain or loss of heat during experiment.
				Commencement of experiment.	Termination of experiment.	
12 Radiation	0	51°·416	0°·483 −	50°·860	51°·006	0°·146 gain
12 Friction.........	1293·25	52·057	0·551 −	51·006	52·006	1·000 gain
13 Radiation	0	51·747	0·246 −	51·456	51·547	0·091 gain
13 Friction.........	1293·25	52·403	0·389 −	51·547	52·482	0·935 gain
14 Friction.........	1293·45	52·703	0·054 +	52·294	53·221	0·927 gain
14 Radiation	0	53·201	0·050 +	53·221	53·281	0·060 gain
15 Friction.........	1293·93	53·644	0·088 +	53·281	54·183	0·902 gain
15 Radiation	0	54·061	0·145 +	54·183	54·230	0·047 gain
16 Radiation	0	51·492	0·318 +	51·821	51·800	0·021 loss
16 Friction.........	1292·83	52·011	0·242 +	51·800	52·706	0·906 gain
17 Radiation	0	51·350	0·055 −	51·272	51·319	0·047 gain
17 Friction.........	1292·83	52·057	0·264 −	51·319	52·268	0·949 gain
18 Friction.........	1292·84	52·576	0·147 +	52·268	53·178	0·910 gain
18 Radiation	0	52·906	0·276 +	53·178	53·187	0·009 gain
19 Radiation	0	50·119	0·142 −	49·928	50·027	0·099 gain
19 Friction.........	1292·33	50·760	0·272 −	50·027	50·950	0·923 gain
20 Friction.........	1293·01	51·004	0·147 −	50·370	51·345	0·975 gain
20 Radiation	0	51·798	0·385 −	51·345	51·482	0·137 gain
21 Radiation	0	52·194	0·646 −	51·482	51·615	0·133 gain
21 Friction.........	1292·83	52·383	0·298 −	51·615	52·555	0·940 gain
22 Friction.........	1292·33	50·389	0·374 +	50·332	51·195	0·863 gain
22 Radiation	0	50·958	0·239 +	51·195	51·199	0·004 gain
23 Radiation	0	51·218	0·498 −	50·636	50·804	0·168 gain
23 Friction.........	1294·69	51·848	0·546 −	50·804	51·800	0·996 gain
24 Friction.........	1294·33	50·582	0·286 +	50·435	51·302	0·867 gain
24 Radiation	0	51·223	0·092 +	51·302	51·328	0·026 gain
25 Radiation	0	51·665	0·406 −	51·190	51·328	0·138 gain
25 Friction.........	1294·33	52·281	0·464 −	51·328	52·306	0·978 gain
26 Friction.........	1294·34	52·652	0·105 +	52·306	53·208	0·902 gain
26 Radiation	0	52·957	0·259 +	53·208	53·225	0·017 gain
27 Friction.........	1293·83	49·463	0·277 +	49·293	50·188	0·895 gain
27 Radiation	0	50·068	0·142 +	50·188	50·233	0·045 gain
28 Radiation	0	48·420	0·145 +	48·537	48·593	0·056 gain
28 Friction.........	1294·33	49·132	0·093 −	48·593	49·486	0·893 gain
29 Friction.........	1294·84	49·142	0·092 +	48·773	49·696	0·923 gain
29 Radiation	0	49·783	0·053 −	49·696	49·765	0·069 gain
30 Radiation	0	50·251	0·422 −	49·765	49·894	0·129 gain
30 Friction.........	1294·33	50·597	0·246 −	49·894	50·808	0·914 gain
Mean Friction ...	1293·532	....	0·00743$\frac{1}{3}$ +	....	....	0·9157 gain
Mean Radiation...	0	....	0·0048 +	....	....	0·0606 gain
1	2	3	4	5	6	7

The effect of each degree of difference between the temperature of the laboratory and that of the apparatus being $0^{\circ}\cdot18544$, $0^{\circ}\cdot9157-0^{\circ}\cdot0606+0^{\circ}\cdot000488=0^{\circ}\cdot855588$, will be the proximate mean increase of temperature in the above series of experiments. The correction, owing to the mean temperature of the mercury in the friction experiments being $0^{\circ}\cdot013222$ higher than appears in the table, will be $0^{\circ}\cdot002452$, which, being added to the proximate result, gives $0^{\circ}\cdot85804$ as the true thermometrical effect. This, in the capacity of 22071·68 grs. of water, is equal to 1° in 2·70548 lbs. of water.

The leaden weights amounted to 137326 grs., from which 1040 grs. must be subtracted for the friction of the pulleys, leaving 136286 grs. as the corrected weight. The mean height of fall was 1293·532 inches, from which 0·047 inch, subtracted on account of the velocity with which the weights came to the ground, leaves 1293·485 inches. This fall, combined with the above corrected weight, is equivalent to 2098·618 foot-lbs., which, with 1·654 foot-lb., the force developed by the elasticity of the string, gives 2100·272 foot lbs. as the mean force employed in the experiments. $\frac{2100\cdot272}{2\cdot70548}=776\cdot303$, will therefore be the equivalent from the above series of experiments, in which the amount of friction of the mercury was moderated by the use of lighter weights.

4th Series of Experiments.—Friction of Cast Iron. Weight of cast iron apparatus, 44000 grs. Weight of mercury contained by it, 204355 grs. Weight of the leaden weights and string attached, 203026 grs. and 203073 grs. Average velocity with which the weights fell, 3·12 inches per second. Time occupied by each experiment, 38 minutes. Thermometer for ascertaining the temperature of the mercury, C. Thermometer for registering the temperature of the air, A.

Table VI.

No. of experiment and cause of change of temperature.	Total fall of weights in inches.	Mean temperature of air.	Difference between mean of columns 5 and 6 and column 3.	Temperature of apparatus.		Gain or loss of heat during experiment.
				Commencement of experiment.	Termination of experiment.	
1 Friction.........	1257·90	46°·362	2°·544 +	46°·837	50°·976	4°·139 gain
1 Radiation	0	46·648	3·950 +	50·976	50·220	0·756 loss
2 Radiation	0	47·296	0·455 —	46·730	46·953	0·223 gain
2 Friction.........	1258·97	47·891	1·247 +	46·953	51·323	4·370 gain
3 Friction.........	1261·80	47·705	1·830 +	47·352	51·718	4·366 gain
3 Radiation	0	48·547	2·950 +	51·718	51·276	0·442 loss
4 Radiation	0	47·825	0·044 —	47·756	47·807	0·051 gain
4 Friction.........	1260·35	48·385	1·598 +	47·807	52·160	4·353 gain
5 Radiation	0	48·323	0·248 —	48·009	48·142	0·133 gain
5 Friction.........	1260·15	48·833	1·494 +	48·142	52·513	4·371 gain
6 Friction.........	1259·95	48·049	1·995 +	47·902	52·186	4·284 gain
6 Radiation	0	48·632	3·283 +	52·186	51·645	0·541 loss
7 Radiation	0	50·385	0·240 —	50·053	50·237	0·184 gain
7 Friction.........	1263·13	51·018	1·408 +	50·237	54·616	4·379 gain
8 Friction.........	1262·12	48·385	1·096 +	47·249	51·714	4·465 gain
8 Radiation	0	49·199	2·343 +	51·714	51·371	0·343 loss
9 Friction.........	1257·20	49·721	2·495 +	50·160	54·273	4·113 gain
9 Radiation	0	50·338	3·643 +	54·273	53·689	0·584 loss
10 Radiation	0	48·439	0·821 +	49·271	49·250	0·021 loss
10 Friction.........	1258·70	49·690	2·282 +	49·877	54·067	4·190 gain
Mean Friction ...	1260·027	....	1·7989+	....	....	4·303 gain
Mean Radiation...	0	....	1·6003+	....	....	0·2096 loss
1	2	3	4	5	6	7

From the above Table, it appears that there was a thermometrical effect of 0°·20101 for each degree of difference between the temperature of the laboratory and that of the apparatus. Hence 4°·303+0°·2096+0°·03992=4°·55252, will be the proximate mean increase of temperature. The correction, owing to the mean temperature of the mercury in the friction experiments appearing 0°·07625 too low in the table, will be 0°·01533, which, added to the proximate result, gives 4°·56785 as the true mean increase of temperature.

The capacity of the apparatus was obtained by experiments made in precisely the same manner that I have already described in the case of the mercurial apparatus for fluid friction. Their results are collected into the following Table.

TABLE VII.

No.	Corrected temperature of water. Commencement of experiment.	Corrected temperature of water. Termination of experiment.	Gain of heat by the water.	Corrected temperature of apparatus. Commencement of experiment.	Corrected temperature of apparatus. Termination of experiment.	Loss of heat by the apparatus.
1	$45^{\circ}\cdot535$	$47^{\circ}\cdot305$	$1^{\circ}\cdot770$	$71^{\circ}\cdot112$	$47^{\circ}\cdot421$	$23^{\circ}\cdot691$
2	46·210	47·937	1·727	71·292	48·073	23·219
3	47·334	49·023	1·689	71·454	49·151	22·303
4	49·007	50·555	1·548	71·152	50·632	20·520
5	47·895	49·498	1·603	71·249	49·636	21·613
6	48·784	50·357	1·573	71·445	50·460	20·985
7	50·323	51·757	1·434	70·793	51·808	18·985
8	47·912	49·525	1·613	71·253	49·653	21·600
9	48·449	50·013	1·564	70·798	50·083	20·715
10	49·836	51·337	1·501	71·356	51·375	19·981
11	46·870	48·559	1·689	71·026	48·657	22·369
12	48·562	50·151	1·589	71·291	50·199	21·092
Mean...	....	....	1·60833	....	....	21·42275

By adding $0^{\circ}\cdot00071$ and $0^{\circ}\cdot0141$, the loss and gain of Table IV. reduced to the surface of the solid-friction apparatus, to the above mean results, we have a gain of $1^{\circ}\cdot60904$ by the water and a loss of $21^{\circ}\cdot43685$ by the apparatus. The capacity of the can of water was in this instance as follows:—

Water	155824 grs.
Copper can as water	1486 grs.
Thermometer and stirrer as ditto	118 grs.
Total . . .	157428 grs.

Hence $\frac{1\cdot60904}{21\cdot43685}\times157428=11816\cdot47$, will be the capacity of the apparatus as tried. By applying the two corrections, one additive on account of the absence during the trials of 300 grs. of mercury, the other subtractive on account of the capacity of the thermometer C and suspending wire, we obtain 11796·07 grs. of water as the capacity of the apparatus during the experiments.

The temperature $4^{\circ}\cdot56785$ in the above capacity, equivalent to 1° in 7·69753 lbs. of water, was therefore the mean absolute quantity of heat evolved by the friction of cast iron.

The leaden weights amounted to 406099 grs., from which 2857 grs., subtracted on account of the friction of the pulleys, leaves 403242 grs. as the pressure applied to the apparatus.

Owing to the friction being in the simple ratio of the velocity, it required a good deal of practice to hold the regulating lever so as to cause the weights to descend to

the ground with anything like a uniform and moderate velocity. Hence, although the mean velocity was 3·12 inches per second, the force with which the weights struck the ground could not be correctly estimated by that velocity as in the case of fluid friction. However, it was found that the noise produced by the impact was on the average equal to that produced by letting the weights fall from the height of one-eighth of an inch. It generally happened also that in endeavouring to regulate the motion, the weights would stop suddenly before arriving at the ground. This would generally happen once, sometimes twice, during the descent of the weights, and I estimate the force thereby lost as equal to that lost by impact with the ground. Taking therefore the total loss at one-fourth of an inch in each fall, we have twenty times that quantity, or 5 inches, as the entire loss, which, subtracted from 1260·027, leave 1255·027 inches as the corrected height through which the weight of 403242 grs. operated. These numbers are equivalent to 6024·757 foot-lbs., and adding 16·464 foot-lbs. for the effect of the elasticity of the string, we have 6041·221 foot-lbs. as the force employed in the experiments.

The above force was not however entirely employed in generating heat in the apparatus. It will be readily conceived that the friction of a solid body like cast iron must have produced a considerable vibration of the framework upon which the apparatus was placed, as well as a loud sound. The value of the force absorbed by the former was estimated by experiment at 10·266 foot-lbs. The force required to vibrate the string of a violoncello, so as to produce a sound which could be heard at the same distance as that arising from the friction, was estimated by me, with the concurrence of another observer, at 50 foot-lbs. These numbers, subtracted from the previous result, leave 5980·955 foot-lbs. as the force actually converted into heat. $\frac{5980{\cdot}955}{7{\cdot}69753}=776{\cdot}997$, will therefore be the equivalent derived from the above experiments on the friction of cast iron. The next series of experiments was made with the same apparatus, using lighter weights.

5th Series of Experiments.—Friction of Cast Iron. Weight of leaden weights, 68442 grs. and 68884 grs. Average velocity of fall, 1·9 inch per second. Time occupied by each experiment, 30 minutes. Thermometer for ascertaining the temperature of the mercury, C. Thermometer for registering the temperature of the laboratory, A.

TABLE VIII.

No. of experiment and cause of change of temperature.	Total fall of weights in inches.	Mean temperature of air.	Difference between mean of columns 5 and 6 and column 3.	Temperature of apparatus. Commencement of experiment.	Temperature of apparatus. Termination of experiment.	Gain or loss of heat during experiment.
1 Friction.........	1281·07	47°·404	0°·852 +	47°·494	49°·018	1°·524 gain
1 Radiation	0	48·003	0·998 +	49·018	48·984	0·034 loss
2 Radiation	0	48·269	0·702 +	48·984	48·958	0·026 loss
2 Friction.........	1280·74	48·516	1·189 +	48·958	50·452	1·494 gain
3 Radiation	0	49·003	0·133 −	48·812	48·928	0·116 gain
3 Friction.........	1285·10	49·728	0·022 +	48·928	50·572	1·644 gain
4 Friction.........	1283·89	50·138	1·172 +	50·572	52·049	1·477 gain
4 Radiation	0	50·408	1·581 +	52·049	51·929	0·120 loss
5 Friction.........	1282·45	46·798	0·558 +	46·554	48·159	1·605 gain
6 Friction.........	1281·29	47·296	1·571 +	48·159	49·576	1·417 gain
5 Radiation	0	47·535	1·929 +	49·576	49·353	0·223 loss
6 Radiation	0	47·651	1·607 +	49·353	49·164	0·189 loss
7 Radiation	0	46·261	0·298 −	45·880	46·047	0·167 gain
8 Radiation	0	46·748	0·617 −	46·047	46·215	0·168 gain
7 Friction.........	1276·07	46·810	0·978 +	47·022	48·554	1·532 gain
8 Friction.........	1275·17	47·366	1·883 +	48·554	49·945	1·391 gain
9 Radiation	0	46·771	0·271 −	46·425	46·575	0·150 gain
9 Friction.........	1276·95	47·126	0·258 +	46·575	48·194	1·619 gain
10 Friction.........	1276·84	47·238	1·655 +	48·194	49·593	1·399 gain
10 Radiation	0	47·335	2·142 +	49·593	49·361	0·232 loss
Mean Friction ...	1279·957	....	1·0138+	....	....	1·5102 gain
Mean Radiation...	0	....	0·764 +	....	....	0·0223 loss
1	2	3	4	5	6	7

From the above Table, it appears that the effect of each degree of difference between the temperature of the laboratory and that of the apparatus was 0°·1591. Hence 1°·5102+0°·0223+0°·03974=1°·57224, will be the proximate heating effect. To this the addition of 0°·00331, on account of the mean temperature of the apparatus in the friction experiments having been in reality 0°·02084 higher than appears in the Table, gives the real increase of temperature in the experiments at 1°·57555, which, in the capacity of 11796·07 grs. of water, is equivalent to 1° in 2·65504 lbs. of water.

The leaden weights amounted to 137326 grs., from which 1040 grs., subtracted for the friction of the pulleys, leaves 136286 grs. The velocity of descent, which was in this case much more easily regulated than when the heavier weights were used, was 1·9 inch per second. Twenty impacts with this velocity indicate a loss of fall of 0·094 inch, which, subtracted from 1279·957, leaves 1279·863 inches as the corrected height from which the weights fell.

The above height and weight are equivalent to 2076·517 foot-lbs., to which the addition of 1·189 foot-lb. for the elasticity of the string, gives 2077·706 foot-lbs. as the

total force applied. The corrections for vibration and sound (deduced from the data obtained in the last series, on the hypothesis that they were proportional to the friction by which they were produced) will be 3·47 and 16·9 foot-lbs. These quantities, subtracted from the previous result, leave 2057·336 foot-lbs. as the quantity of force converted into heat in the apparatus.

$\frac{2057 \cdot 336}{2 \cdot 65504} = 774 \cdot 88$, will therefore be the equivalent as derived from this last series of experiments.

The following Table contains a summary of the equivalents derived from the experiments above detailed. In its fourth column I have supplied the results with the correction necessary to reduce them to a vacuum.

TABLE IX.

No. of series.	Material employed.	Equivalent in air.	Equivalent *in vacuo.*	Mean.
1	Water	773·640	772·692	772·692
2	Mercury	773·762	772·814	774·083
3	Mercury	776·303	775·352	
4	Cast iron......	776·997	776·045	774·987
5	Cast iron......	774·880	773·930	

It is highly probable that the equivalent from cast iron was somewhat increased by the abrasion of particles of the metal during friction, which could not occur without the absorption of a certain quantity of force in overcoming the attraction of cohesion. But since the quantity abraded was not considerable enough to be weighed after the experiments were completed, the error from this source cannot be of much moment. I consider that 772·692, the equivalent derived from the friction of water, is the most correct, both on account of the number of experiments tried, and the great capacity of the apparatus for heat. And since, even in the friction of fluids, it was impossible entirely to avoid vibration and the production of a slight sound, it is probable that the above number is slightly in excess. I will therefore conclude by considering it as demonstrated by the experiments contained in this paper,—

1st. *That the quantity of heat produced by the friction of bodies, whether solid or liquid, is always proportional to the quantity of force expended.* And,

2nd. *That the quantity of heat capable of increasing the temperature of a pound of water (weighed* in vacuo, *and taken at between* 55° *and* 60°) *by* 1° FAHR., *requires for its evolution the expenditure of a mechanical force represented by the fall of* 772 *lbs. through the space of one foot.*

Oak Field, near Manchester,
June 4th, 1849.